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Indirect search for Dark Matter with H.E.S.S.

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Abstract

Observations of the Galactic center region with the H.E.S.S. telescopes have established the existence of a steady, extended source of gamma-ray emission coinciding with the position of the super massive black hole Sgr A*. This is a remarkable finding given the expected presence of dense self-annihilating Dark Matter in the Galactic center region. The self-annihilation process is giving rise to gamma-ray production through hadronization including the production of neutral pions which decay into gamma-rays but also through (loop-suppressed) annihilation into final states of almost mono-energetic photons. We study the observed gamma-ray signal (spectrum and shape) from the Galactic center in the context of Dark Matter annihilation and indicate the prospects for further indirect Dark matter searches with H.E.S.S.

Key words: Dark Matter, Gamma-ray, Extended Air shower observation, Galactic Center

1 Introduction

Observational cosmology has established the existence of non-baryonic Dark Matter as a clear indication for physics beyond the standard model of particle physics. Moreover, the overall matter density is dominated by the contribution of non-baryonic Dark Matter. Despite the good understanding of the cosmological relevance of Dark Matter, its actual nature remains still unknown.
A number of good candidate particles for non-baryonic Dark Matter have been

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suggested in the past: the most intensely studied Dark Matter particle candidate is the Lightest Supersymmetric Particle (LSP) which is predicted in the supersymmetric extension of the standard model of particle physics (Ellis et al. 1984). Even though there is currently no experimental evidence for the existence of supersymmetric partners of standard model particles, there are convincing theoretical arguments to assume that an additional "supersymmetry" exists which e.g. naturally provides a mechanism to break the electroweak symmetry.

While supersymmetric particles have not been found in accelerator based searches, it is expected that the Large Hadron Collider (LHC) at the CERN facility will detect the first evidence for physics beyond the standard model. Beyond the LHC, the next generation International Linear Collider will (if supersymmetry exists) very likely produce precision data on supersymmetric particles and cross sections (Baltz et al. 2006).

Even though an accelerator based discovery of supersymmetry would give strong reasons to assume that Dark Matter is made of supersymmetric particles, it is not a proof that this is the case.

Besides accelerator based experiments to create and find Dark Matter particle candidates in the laboratory, there are two well established approaches to detect Dark Matter already present in the Universe: while direct searches aim at detecting Dark Matter particles as they traverse laboratory experiments, indirect searches aim at finding particles (as e.g. gamma-rays, neutrinos, positrons, and anti-protons) that are produced in the self-annihilation process of Dark Matter particles. Direct and indirect searches for Dark Matter are the only means of tracing Dark Matter in the Universe. While direct Dark Matter searches can only probe the Dark Matter density at the position of the solar system, indirect Dark Matter searches offer the advantage of probing Dark Matter in a wide range of Astrophysical environments including the Center of the Galaxy, Satellite (dwarf) galaxies, black holes environments, nearby Galaxy clusters, as well as the possibility of detecting gamma-ray emission from cosmological Dark Matter annihilation (for an overview see e.g. Bertone et al. 2005).

In this contribution, an overview on the observational results of the Galactic center region with the H.E.S.S. gamma-ray telescopes and their interpretation in the Dark Matter scenario is presented.

2 Observations of the Galactic Center with H.E.S.S.

The H.E.S.S. (High Energy Stereoscopic System) experiment is a ground based facility for the observation of gamma-rays at energies above 100 GeV. The experiment is located in Namibia and consists of an array of four air Cherenkov telescopes positioned at the corners of a square with 120 m side length. The first of the four telescopes has been operational since summer 2002, while the full array has been taking data since the beginning of 2004 (Hinton et al. 2004).

The Galactic center region is one of the prime targets of observation for the H.E.S.S. telescopes. A clear signal from the Galactic center was initially obtained after 17 hrs of data recorded with the first two telescopes in 2003 (Aharonian et al. 2004). The detection of gamma-rays from the Galactic center have also been reported by the CANGAROO (Tsuchiya et al. 2004), VERITAS (Kosack et al. 2003), and the MAGIC collaboration (Albert et al. 2006). The signal observed with the H.E.S.S. telescopes appeared initially spatially unresolved and the measured energy spectrum covered the range from 300 GeV to 10 TeV. A first comparison of the measured energy spectrum with typical self-annihilation spectra indicated that a Dark Matter annihilation scenario could reproduce consistently the observations (Horns 2006). However, the estimated mass of the LSP would have to be uncomfortably high: $m_{\mathrm{LSP}} > 10$ TeV. More data (47.8 hrs) were taken in the following year 2004 and were used to search for Dark Matter annihilation radiation (Aharonian et al. 2006b). With the longer observation time, a more detailed study of the source morphology and energy spectrum was made possible.

As a result of the data analysis, an image of the gamma-ray emission in the central 100 pc of the Galaxy was obtained (see Fig. 1). The gamma-ray emission is dominated by a point-like source located close to the position of Sgr A* and a gamma-ray source coinciding with the position of a composite supernova remnant G0.9+0.1 (Aharonian et al. 2005). After subtracting the contribution of these two sources, a spatially extended excess of gamma-rays following the Galactic ridge is revealed (Aharonian et al. 2006a). The surface brightness of the gamma-ray emission is closely correlated with the molecular gas density as it is inferred from radio observation of CS molecular transitions (see the lower panel of Fig. 1). In a Dark Matter annihilation scenario, an extended source of gamma-ray emission from the central part of the Galactic halo is expected. However, the morphology of an extended Dark Matter annihilation source is expected to be either spherically symmetric or slightly oblate and not to follow the molecular gas density profile.

While the extended gamma-ray emission from the Galactic ridge is very likely produced by cosmic rays penetrating the clouds (Aharonian et al. 2006a), the gamma-ray emission from the point-like source located at the position of Sgr A* could still be related to Dark Matter annihilation processes. In order to study the morphology of this source, the diffuse emission was now subtracted off the excess map. The resulting radial surface brightness profile before and after subtracting the diffuse emission is shown in Fig. 2: the gamma-ray source located at the Galactic center appears spatially unresolved for the H.E.S.S. telescopes. The position of the point-source was determined to be $\alpha = 17^{\mathrm{h}}45^{\mathrm{m}}39.44^{\mathrm{s}} \pm 0.6^{\mathrm{s}}$ and $\delta = -29^\circ 00' 30.3'' \pm 9.7''$ in equatorial coordinates quoting statistical errors only. This is within $7'' \pm 14''_{\mathrm{stat}} \pm 28''_{\mathrm{syst}}$ from the position of Sgr A*.

Based upon the good agreement of the observed radial profile with the expectation of the point-spread function, an upper limit on the extension of the source of $1.2'$ at the 95 % confidence level was derived (Aharonian et al. 2006b).
In a similar approach as used initially by Horns (2006), the observed radial profile is compared with the expectation of a Dark Matter annihilation signal. This is done by folding the point spread function of the instrument with the integrated gamma-ray emissivity from Dark Matter annihilation along the line of sight. The gamma-ray emissivity is proportional to $\rho^2_{\mathrm{LSP}}(r)$, with $\rho_{\mathrm{LSP}}(r)$ indicating the radial Dark Matter density profile. Under the assumption of a power-law type density profile ($\rho_{\mathrm{LSP}} \propto r^{-\alpha}$), the observations can be used to obtain a constraint on $\alpha > 1.2$ (95 % c.l.).
Given that the emission is consistent with a point-like source, the gamma-ray spectrum from the excess events within 0.1° of the position of the source were used to accumulate an energy spectrum. The contamination of the diffuse emission within 0.1° is expected to be a comparably small fraction of 16 % of the total events from the point source. The resulting energy spectrum is shown in Fig. 3 together with the energy spectrum from the data obtained in 2003.
The energy spectrum is well fit with a simple power-law: $dN/dE = N_0(E/1\ \mathrm{TeV})^{-\Gamma}$ with $\Gamma = 2.25 \pm 0.04(\mathrm{stat.}) \pm 0.10(\mathrm{syst.})$. The data obtained in 2003 and 2004 are in good agreement with each other indicating that neither the flux nor the shape of the spectrum have changed with time. The integrated flux above 1 TeV is measured to be $(1.87 \pm 0.10(\mathrm{stat.}) \pm 0.30(\mathrm{syst.})) \times 10^{-12}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. An exponential cut-off below 9 TeV in the energy spectrum is excluded at the 95 % c.l.
A search for variability on different time-scales has been carried out on the available data from 2003 and 2004. No indications for variability have been found.

3 Dark Matter interpretation for the Galactic center signal

Under the assumption that all the gamma-ray emission observed from the Galactic center source is produced via Dark Matter annihilation, it is interesting to compare the shape of the observed gamma-ray spectrum with the one expected from Dark Matter annihilation.
It is obvious, that the observation of a gamma-ray signal up to 10 TeV would require a sufficiently massive LSP. Furthermore, the observed energy spectrum appears to follow a smooth power-law without indications for curvature. A curved energy spectrum is however expected for the most commonly considered supersymmetric models like Minimal Supersymmetric extension of the Standard Model (MSSM) (see e.g. Ellis et al. 2002), Anomalously mediated

Symmetry Breaking (AMSB) (see e.g. Profumo & Ullio 2004), or Kaluza-Klein (KK) (see e.g. Servant & Tait) scenarios with extra-dimensions.
The fact that the required mass of the LSP is larger than 10 TeV leads to an additional hard radiative component as suggested by Bergström et al. (2006). Additionally, some fine-tuning of the model-specific branching ratios for the annihilation processes can be used to produce a harder energy spectrum (Profumo 2006). A number of different Dark Matter annihilation spectra including a KK spectrum are shown in Fig. 3 together with the measurements. It is evident, that the data and the considered models do not agree.
In a different approach, we assume that the observed gamma-ray emission is predominantly emitted by a possible "conventional" gamma-ray source which produces a typical power-law type energy spectrum. Now, we can vary the mass and the annihilation rate of the LSP to evaluate the maximum annihilation rate for a given mass that does not violate the measured energy spectrum. Following this approach, upper limits on the annihilation rate can be obtained. The upper limits derived through this method are not severely constraining the annihilation cross section because of the large uncertainties on the Dark Matter halo density which can be as large as three orders of magnitude.

4 Summary and Outlook

The indirect search for Dark Matter using gamma-rays offers a unique way of probing the Dark Matter density in the Universe. The new ground based gamma-ray telescopes like H.E.S.S. have in principle achieved sufficient sensitivity to detect gamma-ray emission from the annihilation of Dark Matter. The drawback of this technique is the difficulty to disentangle the contribution of Dark Matter annihilation radiation from the emission of conventional gamma-ray sources. The example of the gamma-ray source in the Galactic center demonstrates clearly these difficulties.
Whatever the origin of the gamma-ray emission from the Galactic center is, observations at energies below 100 GeV and above 10 TeV are of crucial importance in order to determine the dominant gamma-ray production mechanism. The H.E.S.S. installation is currently extended ("Phase II") to include a Large Cherenkov Telescope (LCT) which will extend the accessible energy range of H.E.S.S. to energies as low as 20 GeV. This energy range is also accessible with the GLAST satellite. In a few years from now, the gamma-ray spectrum from the Galactic center source is expected to be measured from energies below 1 GeV up to energies well beyond 10 TeV, covering a total of four decades in energy. At the same time, the accelerator experiments of the LHC will provide the first indications and/or constraints on supersymmetric particles.
The indirect search for gamma-ray emission from Dark Matter annihilation using H.E.S.S. Phase II, GLAST, as well as the coming generation of acceler-

ator experiments will provide us with a clear and detailed view on the elusive Dark Matter particle.

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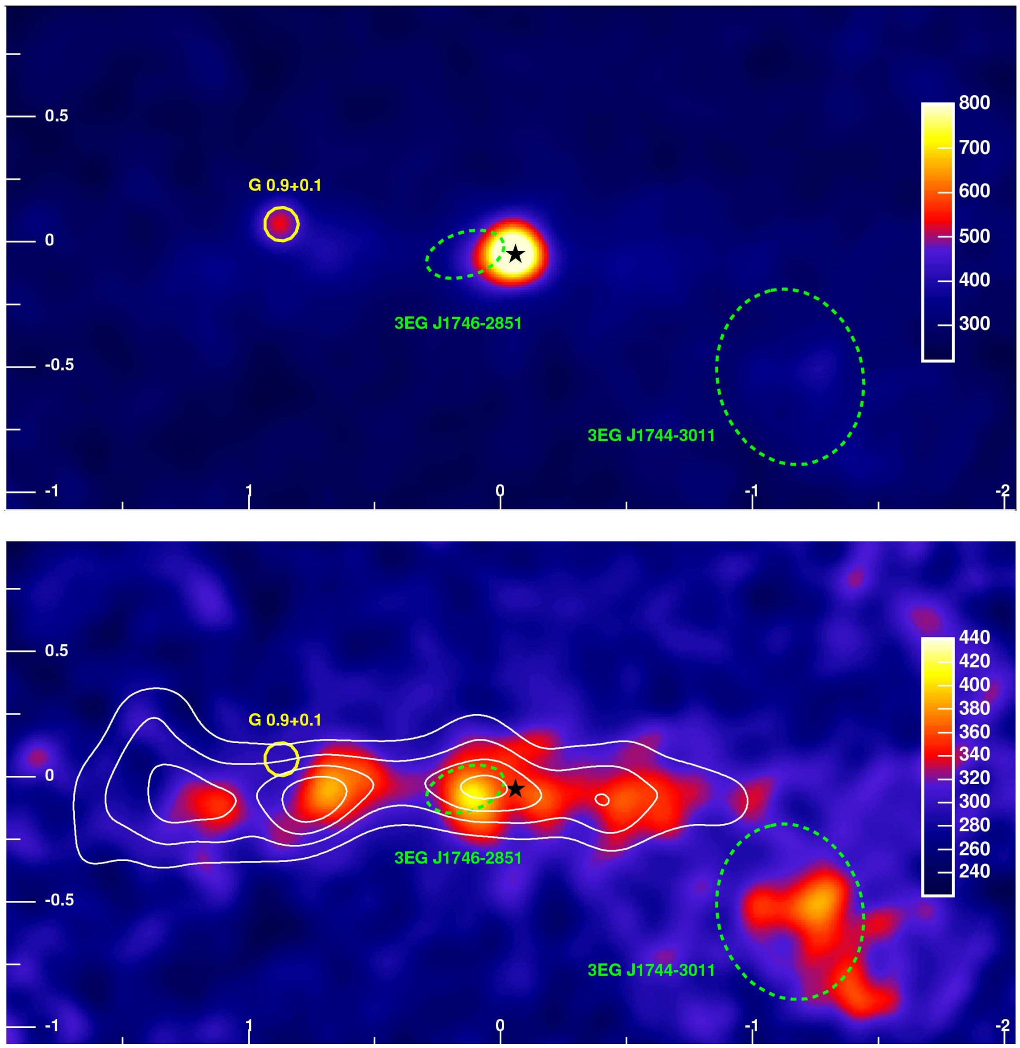

Fig. 1. The upper panel shows the smoothed excess map dominated by the signal from the Galactic center and from the composite supernova remnant G0.9+0.1. After subtracting the contribution from these two sources, an extended emission feature is apparent (lower panel) which correlates well with the molecular gas density (white contours: smoothed molecular gas density derived from measurements of CS molecular line transitions (Tsuboi et al. 1998)). The star marks the position of Sgr A*, the dashed ellipses indicate the 95 % confidence region of EGRET sources (Mattox et al. 2001) located in the Galactic center region.

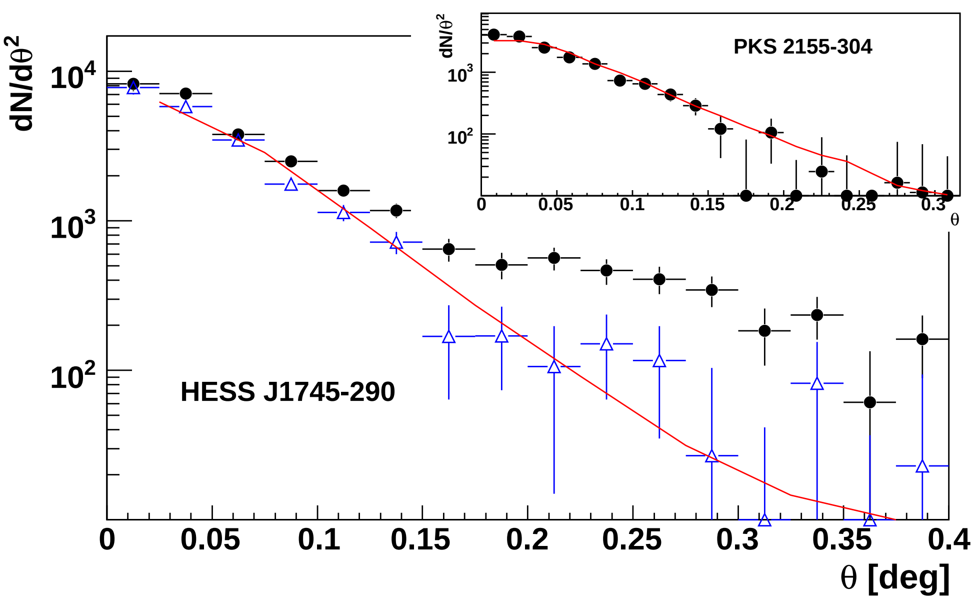

Fig. 2. Radial surface brightness profile of the gamma-ray emission (number of gamma-ray events per solid angle) from the Galactic center: The solid points indicate the number of gamma-ray events detected from the Galactic center and the environment up to an angular separation of $\theta = 0.4^\circ$ while the open points show the surface brightness after subtracting off the diffuse emission from the Galactic ridge. The solid line represents the expected distribution of gamma-rays for a point-like source taking into account varying zenith angles of the observation. As an example for an observation of a point-like source, the signal obtained from the Active Galactic Nucleus PKS 2155-304 is shown in the inlaid figure.

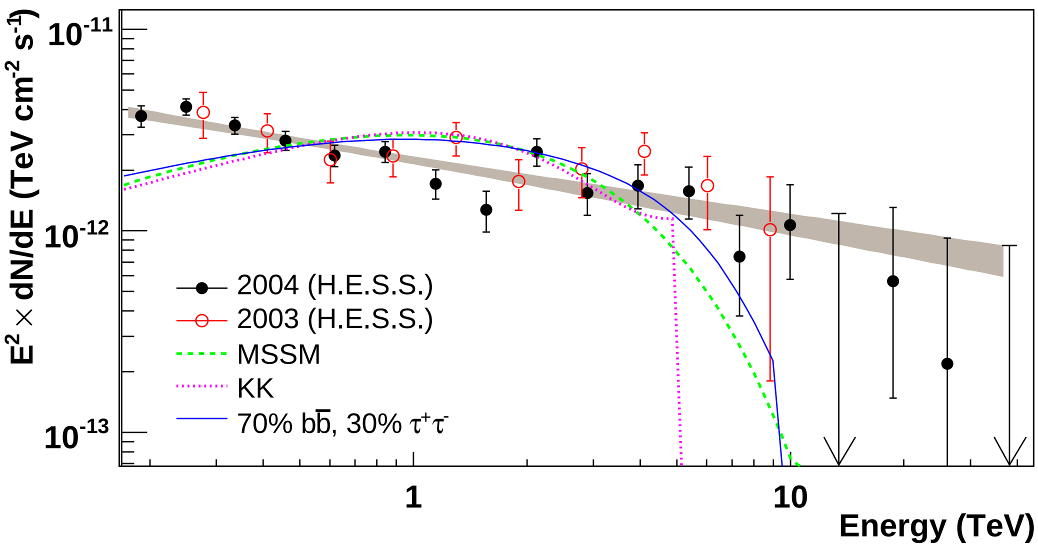

Fig. 3. Energy spectrum from the point-like source in the Galactic center: the open points are derived from the smaller data-set taken in 2003 while the closed points indicate the energy spectrum as measured in 2004. The two measurements indicate that the source is steady in time. The shaded region shows the power-law fit $dN/dE \propto E^{-\Gamma}$ including the statistical uncertainties. The dashed line presents a typical MSSM Dark Matter annihilation spectrum for a best-fit LSP mass $m_{\mathrm{LSP}} = 14$ TeV. The dotted line gives the annihilation spectrum for a Kaluza-Klein type Dark-Matter particle with a mass of 5 TeV while the solid line is the annihilation spectrum of an LSP with a mass of 10 TeV that annihilates with a specific branching ratio of 70 % into $b\bar{b}$ and 30 % into $\tau^+\tau^-$.